Identification of Requirements for Material Balance Evaluation based on a Benchmark Scenario

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1. Introduction

The ROK has been conducting independent national inspection to domestic nuclear facilities since 2015. The domestic notification (NSSC notification No.2017-83) indicates national inspection should include the verification of material accounting uncertainty [1].

The Korea Institute of Nuclear non-proliferation and Control (KINAC) on behalf of the Nuclear Safety and Security Commission (NSSC) of the ROK, is performing independent national inspection to domestic nuclear facilities, including book examination and inventory verification. However, the entire material balance evaluation (MBE) for bulk handling facilities has not conducted yet.

The purpose of the paper is to perform a MBE for a fuel fabrication plant using a benchmark scenario. We calculated the material unaccounted for (MUF) and the uncertainty of the MUF (σ_{MUF}) using the characteristics of the benchmark facility and the modified previous inspection data on domestic fuel fabrication plants. Results indicated the MUF of the facility was originated from the uncertainty of the measurement system.

We identified requirements for independent material balance evaluation using the results of the benchmark MBE scenario. It includes the stratification rule, detailed measurement system and the List of Inventory Items (LII) of the facility.

2. Material Balance Evaluation

Nuclear facilities can be classified into an item counting facility and bulk handling facility. An item counting facility is a facility where every nuclear material is controlled within an item, whereas a bulk handling facility includes the physical and chemical conversion of nuclear material. The physical inventory in a bulk handling facility has to be verified since it should have material loss or gain due to the measurement system.

The material unaccounted for (MUF) is the difference between the reported mass in the book and the measured mass. The MUF of bulk handling facilities cannot be zero due to the measurement error and material loss during the physical and chemical conversion. The MUF within a material balance area (MBA) is calculated using equation (1). The book inventory of the MBA at the end of the MBP is the sum of beginning inventory and material net flow, material inflow minus outflow [2].

$$\mathrm{MUF} = \mathrm{PB} + \mathrm{X} - \mathrm{Y} - \mathrm{PE} \quad (1)$$

where,
MUF: Element/isotope material unaccounted for,
PB: Physical inventory at the beginning of an MBP,
X: Material inflow, Y: Material outflow,
PE: Physical inventory at the end of an MBP.

We calculated the book inventory and measured inventory of a benchmark facility using the general ledger and the list of inventory item (LII) of a previous inspection (2016) on a fuel fabrication plant. The design information and the uncertainty of the measurement system of the facility were estimated based on general process of PWR fuel fabrication plants.

We made a material balance table (MBT) using the LII and stratification rule. The stratification rule for the nuclear material in the facility is the same with the IAEA's stratification rule on the ROK's fuel fabrication plant. The uncertainty of measurement systems was estimated using the declared information and ITV 2010 results [4].

The MUF was calculated using the results of the general ledger and MBT. The individual MUF uncertainty (random, short-term systematic, systematic) of each stratum was also calculated using the design information and measurement uncertainty. We combined the individual MUF uncertainty to calculate the total MUF uncertainty. The random, short-term systematic and systematic isotope MUF uncertainty is calculated using equations (2) to (4) [3]. The element MUF is calculated using the same equation except for isotopic analysis term.

$$\mathrm{V_r}(\mathrm{MUF}) = \sum_{k=1}^{K} x_k^2 \left(\frac{\delta_{rq}^2}{n_k m_k} + \frac{\delta_{rp}^2}{r_k^* m_k} + \sum_{g(k)=1}^{G(k)} \left(\frac{\delta_{rt(E)}^2}{c_k r_k m_k} + \frac{\delta_{rt(I)}^2}{c_k^* r_k^* m_k} \right) \right) \quad (2)$$

$$\mathrm{V_g}(\mathrm{MUF}) = \sum_q \delta_{gq}^2 \sum_i M_{qi}^2 + \sum_p \delta_{gp}^2 \sum_i M_{pi}^2 + \sum_{t(E)} \delta_{gt(E)}^2 \sum_i M_{t(E)i}^2 + \sum_{t(I)} \delta_{gt(I)}^2 \sum_i M_{t(I)i}^2 \quad (3)$$

$$\mathrm{V_s}(\mathrm{MUF}) = \sum_q \delta_{gq}^2 M_q^2 + \sum_p \delta_{gp}^2 M_p^2 + \sum_{t(E)} \delta_{gt(E)}^2 M_{t(E)}^2 + \sum_{t(I)} \delta_{gt(I)}^2 M_{t(I)}^2 \quad (4)$$

where,
$\mathrm{V}_{r/g/s}(\mathrm{MUF})$: MUF variance due to random/short-term systematic /systematic error,
x_k: Isotope mass of stratum k, K: Number of strata in the facility,
$\delta_{(r/g/s)\,(q/p/t(E)/t(I))}$: Relative uncertainty of analysis method,
n_k: Item per batch in stratum k,
$r_k^{(*)}$: Sample per batch in stratum k for element (isotope) analysis,
m_k: Batch per stratum k,
$c_k^{(*)}$: Analysis per sample in stratum k for element (isotope) analysis,
$\mathrm{M}_{q/p/t(E)/t(I)} = \sum_{k=1}^{K} A_k x_{kq/p/t(E)/t(I)}$,
A_k: +1 for gain, -1 for loss.

We then compared the total MUF uncertainty to the calculated MUF using a statistical hypothesis testing(z-test, ($H_0: MUF = 0,\ H_1: MUF \neq 0$). We adopted z=3, which is identical to the IAEA's standard, for the confidence interval.

3. Benchmark Case

The fuel fabrication plant used in the paper was a typical PWR fuel fabrication plant, which includes (re)conversion, sintering, fuel rod and assembly fabrication process. The relative uncertainty of each measurement system is described in Table 1.

We assumed the following assumptions for the benchmark facility:

1. The bulk measurement uncertainty is consistent for the materials in the same storage
2. The sampling uncertainty is consistent for the same compounds (element analysis)
3. The element (isotope) analysis uncertainty is consistent for the material with the same chemical composition (material type (UO_2, clean scrap, dirty scrap))
4. The material with different physical and chemical characteristics has short-term systematic bulk measurement error
5. The material with different physical/chemical characteristics and enrichment has short-term systematic sampling error
6. The material with different physical characteristics and location has short-term systematic element (isotope) analysis error

Table 2. Relative error of the bulk measurement, element(p(E))/isotope(p(I)) sampling, element(t(E))/isotope(t(I)) analysis

	δ_rq..			
0	dummy			0
1	EBAL(FA)			0.001
2	EBAL(QC room)			0.0005
3	EBAL(U storage)	1	Fuel rod	0.0005
		2	UO2 pellet	0.0005
		3	Conversion products - Plant 2	0.0005
		4	Pellet & Scrap Storage - Plant 2	0.0005
4	EBAL(UF6 cylinder) - Plant 1			0.001
5	EBAL(UF6 cylinder) - Plant 2			0.001
6	EBAL(Gd PL/PD storage) - Plant 1	1	Powder	0.0005
		2	Pellet	0.0005
		3	Scrao	0.0005
7	EBAL((Re) conversion process) - Plant 2	1	Powder	0.0005
		2	(Re) Conversion Products	0.0005
8	EBAL(Reconversion Powder Storage)	1	Powder	0.0005
		2	Scrap	0.0005
9	EBAL(Gd rod Production) - Plant 1			0.0005
10	EBAL(Pellet Production Process) - Plant 2	1	Pellet	0.0005
		2	Scrap	0.0005
11	EVAL(Pellet&Scrap Storage) - Plant 2	1	Pellet	0.0005
		2	Scrap	0.0005
12	EBAL(Inspection Lab) - Plant 1			0.0005
13	EBAL(Inspection Lab) - Plant 2			0.0005
14	EBAL(Gd pellet production process) - Plant 1			0.0005
15	EBAL(U Storage) for samples - Plant 1			0.0005

	δ_r.p_E.			
0	dummy			0
1	UO2 powder/pellet(pure)	1	Powder	0.0005
		2	Pellet	0.0005
2	UO2 pellet(gd)			0.001
3	Clean Scrap			0.001
4	Dirty Scrap			0.01
	δ_r.p_I.			
0	dummy			0
1	UO2 powder/pellet(pure)	1	Powder/Pellet - 1.28	0.0005
		2	Powder/Pellet - 1.4	0.0005
		3	Powder/Pellet - 1.6	0.0005
		4	Powder/Pellet - 1.72	0.0005
		5	Powder/Pellet - 2.0	0.0005
		6	Powder/Pellet - 2.2	0.0005
		7	Powder/Pellet - 2.35	0.0005
		8	Powder/Pellet - 2.45	0.0005
		9	Powder/Pellet - 2.65	0.0005
		10	Powder/Pellet - 2.92	0.0005
		11	Powder/Pellet - 3.1	0.0005
		12	Powder/Pellet - 3.15	0.0005
		13	Powder/Pellet - 3.42	0.0005
		14	Powder/Pellet - 3.5	0.0005
		15	Powder/Pellet - 3.62	0.0005
		16	Powder/Pellet - 3.92	0.0005
		17	Powder/Pellet - 4.0	0.0005
		18	Powder/Pellet - 4.1	0.0005
		19	Powder/Pellet - 4.42	0.0005
		20	Powder/Pellet - 4.5	0.0005
		21	Powder/Pellet - 4.65	0.0005
2	UO2 pellet(gd)	1	Gd Pellet/powder storage - 2.6	0.0007
		2	Pellet - 2.0	0.0007
		3	Pellet - 2.22	0.0007
3	Clean Scrap			0.001
4	Dirty Scrap			0.01

	δ_r..t_E			
0	dummy			0
1	TGA(UO2)	1	powder	0.0005
		2	pellet	0.0005
2	TGA(UO2+Gd)	1	Gd pellet/powder storage	0.0005
		2	U storage	0.0005
3	TITR	1	Lab Sample	0.001
		2	Clean Scrap	0.001
		3	Dirty Scrap	0.001
	δ_r..t_I			
0	dummy			0
1	TIMS_LEU	1	UO2 powder	0.001
		2	UO2 pellet	0.001
		3	UO2 pellet with Gd	0.001
		4	Samples in analysis laboratory	0.001
2	Clean Scrap(TIMS)			0.001
3	Dirty Scrap(TIMS)			0.001

4. Results

We calculated the random uncertainty for each stratum, short-term systematic uncertainty for each short-term identical method and systematic uncertainty for each method using the benchmark case information. We then combined the individual uncertainty factor to calculate the uncertainty of element and isotope MUF (Table 3).

The element and isotope MUF uncertainty were then compared to the MUF (Table 4). Results of Table 4 indicates the amount of element and isotope MUF are smaller than 3 times of MUF uncertainties. As a result, given that the false alarm probability is 0.374 % (z=3), the MUF in the benchmark facility was originated from the measurement uncertainty.

Table 3. Calculated element and isotope MUF uncertainty

u(MUF,Element) (kg)	V(MUF,Element) (kg^2)	Vr(MUF)	Vg(MUF)	Vs(MUF)
494.940	244965.257	9818.667	12948.345	222198.244
u(MUF,Element) (kg)	**V(MUF,Element) (kg^2)**	**Vr(MUF)**	**Vg(MUF)**	**Vs(MUF)**
18.667	348.463	1.681	29.349	317.433

Table 4. Evaluation of MUF uncertainty to MUF

	Measured Inventory	Book Inventory
U Weight (KG):	1,022,096.481	1,023,082.848
U235 Weight (KG):	38,572.800	38,548.731
MUF (kg)	**σ(MUF) (kg)**	**Significance(3σ)**
986.367	494.9396499	No
-24.069	18.66716368	No

5. Conclusions

We examined the feasibility of MBE using the IAEA's statistical method, benchmark facility characteristics and estimated list of inventory items. The paper examined the feasibility of applying the MBE method on a domestic facility and identified requirements for domestic safeguards inspection.

Results of the benchmark MBE identified the requirements for applying MBE as a part of national inspection. The requirements were:

1. Optimized stratification rules to the list of inventory items for MBEs
2. Inspection support program which performs the formatting of operator declared information and inspection planning
3. Detailed characteristics (or design information) on the process and measurement system of a target facility
4. Establishment of the evaluation criteria (i.e. confidence level optimization and CUMUF test for a series of MBPs)
5. Examination of $\left(\mathrm{MUF} - \widehat{D}\right)$ and $\widehat{D}$ test to evaluate the operator-inspector difference and inspector's measurement system

Future works will be conducted to satisfy the identified requirements.

REFERENCES

[1] Subparagraph 7 of Article 4 of Regulations on the Safeguards Inspection of Special Nuclear Materials of the ROK, NSSC notification No. 2017-83, 2017.
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